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Uniform and Non-Uniform Second-Best Input Taxes

The Significance of Market Price Effects on Efficiency and Equity[⋆]

ROGER CLAASSEN[1] and RICHARD D. HORAN[2]
[1]*Resource and Environmental Policy Branch, Resource Economics Division, Economic Research Service, USDA, Washington, DC 20036-5831, USA (E-mail: claassen@ers.usda.gov);* [2]*Department of Agricultural Economics, Agriculture Hall, Michigan State University, East Lansing, MI 48824-1039, USA (E-mail: horan@msu.edu)*

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Abstract. We investigate second-best, input-based taxes for agricultural nonpoint pollution control when market prices are endogenous and production is heterogeneous. Theoretically, we derive the optimal forms of taxes which take account of heterogeneity (non-uniform taxes) and a tax which does not (a uniform tax). Empirically, we use a multi-factor, market-equilibrium simulation model to determine optimal tax rates and associated equity effects, particularly differences in landowner gains/losses across a heterogeneous region. When market prices are endogenous, second-best tax policies result in pecuniary externalities that affect existing environmental externalities. In particular, the pecuniary externalities amplify the effect of producer heterogeneity on determination of sub-regional differences in tax rates and returns to land, particularly for the uniform policy. With endogenous prices, the uniform tax rate is considerably higher than any of the non-uniform rates and, ironically, the non-uniform taxes result in less dispersion of landowner gains across sub-regions than the uniform tax.

Key words: equity, fertilizer tax, heterogeneity, input-based tax, nutrient runoff, nonpoint pollution, second-best

JEL Classification: Q28

Agricultural nonpoint source pollution, especially nutrient runoff, has been identified as a major source of many remaining U.S. water quality problems (USEPA and USDA 1998). Future pollution control programs are likely to place greater emphasis on the use of economic incentives and enforceable mechanisms to reduce nonpoint pollution (USEPA and USDA 1998). Yet a variety of significant economic questions regarding the efficiency and equity of alternate incentive mechanisms remain.

In this paper, we explore differences in the relative efficiency and equity of uniform and non-uniform second-best input taxes designed to reduce agricultural

[⋆] The views expressed here are those of the authors and do not necessarily reflect those of the Economic Research Service or USDA.

nutrient emissions when production is heterogeneous and market prices are endogenous. (As we describe below, second-best in this context implies that taxes are applied to only a subset of inputs affecting emissions, possibly at uniform rates. See Shortle et al. 1998) First, the optimal forms of these taxes are presented to provide a conceptual understanding of optimal policy design under these conditions and to allow for comparison with previous research that does not account for endogenous prices. Next, we develop a regionalized, market equilibrium model of corn production and associated nutrient emissions in the North Central U.S. Optimal policies are determined and their relative efficiency and equity impacts are assessed.

We find that optimal second-best tax rates and landowner surplus are substantially higher, and differences between a uniform tax policy (which does not recognize heterogeneity) and non-uniform policy (which does recognize heterogeneity) are substantially larger when market prices are endogenous. The input and output market price effects produced by the input tax policy result in pecuniary externalities (externalities that are the result of changes in input and output prices, see Baumol and Oats 1988, p. 29) that amplify the effect of technological heterogeneity in determining differences in tax rates and returns to land. The amplification effect is especially large for the uniform tax and contributes significantly to differences between uniform and non-uniform tax policies. Compared to the non-uniform tax, the uniform tax produces (1) substantially larger control cost (i.e. the reduction in net private surplus); (2) greater divergence between landowner gains (in aggregate) and loses to other groups in society; and (3) greater divergence in returns among landowners in the various subregions modelled in our study. Our results suggest that even small variations in sub-regional tax rates can be important in holding down overall costs and reducing the dispersion of returns among landowners and between land owners and other groups.

These results produce at least two important insights on the selection of uniform versus non-uniform policy for agricultural nutrient runoff reduction. First, because the non-uniform, second-best fertilizer tax significantly outperforms a uniform tax in terms of control cost, any differences in transactions costs or administrative burden between the two policies must be substantial in order to justify use of the uniform policy. Second, even if use of the uniform tax policy can be justified on the basis of transaction cost or administrative burden, it cannot be justified on the basis of equity. While it is sometimes argued that uniform policy is more equitable, at least for producers and other owners of agricultural resources, our results suggest that just the opposite may be true: uniform policies produce greater divergence in returns both within agriculture and between agriculture and the consumers of agricultural commodities.

Previous Research

Nonpoint pollution policy design is complicated by the typically unobservable and stochastic nature of nonpoint source emissions as well as the site-specific nature of nonpoint problems (Braden and Segerson 1993; Shortle and Abler 1997). These and other characteristics of nonpoint problems limit the range of potential policy instruments and also the efficiency of many remaining options. Among feasible instruments, input-based incentives are potentially effective tools with economically desirable characteristics (e.g., Shortle, Horan and Abler 1998; Shortle and Abler 1997; Helfand and House 1995; Larson, Helfand and House 1996). However, efficient policies may ultimately be unworkable. Efficient nonpoint pollution control requires input-based instruments to be applied to all inputs influencing emissions and varied across regions and farms due to heterogeneity in production and environmental effects (Shortle and Abler 1997; Flemming and Adams 1997). This may be administratively difficult and costly (Shortle, Horan and Abler 1998; Larson, Helfand, and House 1996), especially given the often extreme spatial variation in the agricultural resource base (particularly land) (Braden and Segerson 1993; Shortle and Abler 1997). Alternatively, second-best policies may target only a few inputs that influence emissions, and/or may be applied uniformly across producers (Helfand and House 1995; Larson, Helfand and House 1996; Shortle, Horan and Abler 1998).

Moreover, because agricultural nonpoint problems are widespread, comprehensive solutions are likely to impact markets for both agricultural outputs and inputs. However, little work has been done to characterize market equilibrium effects when policy instruments are endogenously tied directly to environmental performance, production is heterogeneous, and a variety of factors are used in production. Gardner (1987) has characterized the potential market equilibrium and equity effects of exogenously applied input taxes using a one-output, two-input model with homogeneous production. Empirical work on second-best, input-based incentives (e.g., Helfand and House 1995; Larson, Helfand and House 1996; Taylor, Adams and Miller 1992; Flemming and Adams 1997; Hopkins, Schnitkey and Tweeten 1996) generally incorporates significant detail on heterogeneity within the study area, but the areas are often (by design) too small to produce appreciable market effects.

Most prior empirical work has considered only total economic surplus or consumer and producer surplus rather than gains and/or losses associated with specific resources such as land (Helfand and House 1995; Larson, Helfand and House 1996). Ultimately, however, policy interventions affect the returns to productive resources (Floyd 1965; Gardner 1987). Given the long-standing and well-documented importance of farmer economic interests in the formulation of agricultural policies, productive resources owned by farmers will be of particular concern to policy makers. Land is arguably the single most important factor that is widely owned by farmers, as well as a significant source of heterogeneity in agricultural production. Empirical evidence suggests that past commodity program benefits have been significantly capitalized into land values (Herriges, Barickman and Shogren 1992; Duffy et al. 1994), implying that landowners’ interests have been important to policy makers.

Equity considerations related to second-best policies may be especially important. For example, uniform policies are often preferred in practice because they are easier (and, presumably, less costly) to administer, and seemingly more fair to the agricultural producers and resource owners to whom the policies are directed. These assumptions may not be valid, however, when the resource base is heterogeneous and market prices are endogenous. Indeed, Lichtenberg, Parker and Zilberman (1988) show compliance costs under uniformly applied pesticide use regulations can vary significantly over producers and resource conditions. The potential for variation in economic consequences may be particularly large now that the Federal Agricultural Improvement and Reform (FAIR) Act has largely decoupled farm income support payments from commodity prices. In the past, income support (deficiency) payments made up the difference between a Congressionally mandated "target" price and the market price for major commodities, effectively insulating producers from commodity market fluctuations (Lichtenberg and Zilberman 1986). With decoupling, the price effects of agri-environmental policies may impact agricultural producers. Thus, a uniformly applied policy may increase net returns for some producers and decrease net returns to others, depending on the nature of the policy-induced price effects.

A Model of Production and Nonpoint Pollution

Our model closely follows that of Shortle et al. (1998), with the exception that we treat prices as endogenous. Suppose a specific agricultural commodity (corn) is produced in a particular geographical region. Without loss of generality, we consider aggregate production in each of *n* exogenously defined sub-regions (our qualitative results are the same as if *n* represented the number of farms in the region). Denote production in the *i*th sub-region by the concave function $f^i(x^i)$, where x^i is an $(m \times 1)$ vector of inputs (*j*th element x^i_j). The price of corn is *p*, with inverse demand $p(y)(p' < 0)$. Define x^i_1 to be acres of land devoted to corn, supplied according to a sub-regional inverse supply $w^i_1 = w^i_1(x^i_{1s})(\partial w^i_1/\partial x^i_{1s} > 0)$. All other inputs are supplied according to a regional inverse supply $w_j = w_j(x_j)(w'_j \geq 0 \forall j)$. Producers in sub-region *i* are price-takers operating in competitive input and output markets, with profits $\pi^i(x^i) = pf^i(x^i) - \sum_{j=1}^m w_j x^1_j$.

Given the market clearing conditions $y = \sum_{i=1}^n f^i$, $x^i_1 = x^i_{1s} \forall i$, and $x_j = \sum_{i=1}^n x^i_j (j = 2, \ldots, m)$, and assuming income and substitution effects are small, net private surplus is (Just et al. 1982)

$$V = \int_0^y p(z)dz - \sum_{i=1}^n \int_0^{x^i_1} w^i_1(z)dz - \sum_{j=2}^m \int_0^{x_j} w_j(z)dz \tag{1}$$

Corn production creates external social costs through the unintended generation of NPS emissions. Denote sub-region *i*'s per acre emissions (henceforth, runoff) by $r^i = r^i(g^i, v^i)$, which for simplicity depends only on fertilizer use per acre, $g^i =$

x_2^i/x_1^i (x_2^i is aggregate fertilizer use in sub-region i), and stochastic environmental impacts, v^i.[1] Sub-region i's aggregate runoff is $x_1^i r^i$.

Nonpoint Management with Second-Best Input-Based Incentives

Efficient nonpoint pollution management requires knowledge of external social costs and the fate and transport of pollutants once they have left the farm – items which are often largely unknown (Shortle et al. 1998). An alternative approach is to achieve an environmental objective cost-effectively, choosing policies to maximize (1) subject to a constraint implied by the objective (Baumol and Oates 1988). The environmental objective we consider, which is consistent with existing nonpoint pollution policy goals (see e.g., USEPA and USDA 1998), is a reduction in expected runoff, i.e.,

$$E\{r^i x_1^i\} \leq \kappa^i \quad \forall i \tag{2}$$

where κ^i is a constant.[2] We focus on individual goals for each sub-region so that, in the empirical model below, all interactions between sub-regions occur through input and output markets. This allows us to focus more clearly on the impacts of market price effects on policy design and the resulting economic consequences.

The policy options we consider are input-based incentives. A least cost (first-best) input-based policy would vary by source and would target both fertilizer applications and land use since only these production choices influence runoff. In practice, however, incentives may be based on a limited set of inputs that influence runoff and/or applied at uniform rates across producers due to transactions costs or other considerations (Helfand and House 1995; Larson et al. 1996; Shortle et al. 1998). We consider two such policies that have been proposed in the NPSP literature: uniform and non-uniform fertilizer taxes, with no other instruments targeted at land use (e.g., Shortle et al. 1998; Helfand and House 1995; Larson et al. 1996). These policies can only be second-best, that is, designed to satisfy (2) at least cost given the restrictions on the manner in which they are implemented (i.e., uniform versus non-uniform, not targeting land use). These restrictions create inefficiencies that prevent second-best policies from providing the least cost solution over all policy options.[3]

It is not possible to control all substitution, output, and market price effects when land is not targeted along with fertilizer because land prices are not optimally controlled. Instead, a fertilizer tax creates (positive or negative) environmental externalities in the sub-region to which it is applied as producers substitute away from fertilizer towards land. We refer to this type of externality as a substitution externality for simplicity and to distinguish it from traditional environmental externalities stemming from market failure.

Furthermore, tax induced substitution and output effects of producers in one sub-region affect market prices and, hence, producers in other sub-regions. We refer to these effects as "pecuniary externalities" because they are transmitted through markets, rather than directly among producers or producers and consumers directly. These pecuniary externalities, which occur both for the uniform and the non-uniform fertilizer tax cases, have two effects. The first effect, market price effects that directly impact producers' profits, only has equity impacts and is thus not considered relevant in terms of efficiency (Baumol and Oates 1988). The second effect is relevant in terms of efficiency. Market price effects impact environmental externalities in other sub-regions by altering social pollution control costs and hence the level of pollution control in these other areas.[4] Henceforth, our use of the term pecuniary externality refers only to this second effect. As we show below empirically, pecuniary externalities can have important economic implications.

Because they are designed optimally, second-best taxes take both substitution and pecuniary externalities into account. This can be seen in the optimal forms of these taxes (unlike first-best taxes in which all relative prices are set to optimally control all substitution, output, or market effects (Shortle et al. 1998)). All derivations are provided in the Appendix.

First, consider the optimal non-uniform fertilizer tax[5]

$$t^i = \lambda^i E\left\{\frac{\partial r^i}{\partial g^i}\right\} - \lambda^i \left(E\left\{\frac{\partial r^i}{\partial g^i}\right\} g^i - E\{r^i\}\right)\omega_1^{ii} + \sum_{k\neq i}\lambda^k E\left\{\frac{\partial r^k}{\partial g^k}\right\}\zeta^{ki} - \sum_{k\neq i}\lambda^k\left(E\left\{\frac{\partial r^k}{\partial g^k}\right\} g^k - E\{r^k\}\right)\omega_1^{ki}\zeta^{ki} - \sum_{k\neq i} t^k\zeta^{ki} \quad \forall i \qquad (3)$$

where $\omega_j^{ki} = (dx_j^k/dt^i)/(dx_2^k/dt^i)$, $\zeta^{ki} = (dx_2^k/dt^i)/(dx_2^i/dt^i)$, and all RHS values are evaluated at the second-best optimum. The first term on the RHS of (3), $\lambda^i E\{\partial r^i/\partial g^i\}$, is of the same form as the first-best tax, although it is evaluated at the second-best optimum. The remaining terms reflect adjustments that optimally take into account the additional substitution and pecuniary externalities created by the tax since land use is not targeted.

The first adjustment term, $-\lambda^i(E\{\partial r^i/\partial g^i\}g^i - E\{r^i\})\omega_1^{ii}$, deals with the substitution externality. Assuming land and fertilizer are net substitutes (i.e., $\omega_1^{ii} < 0$) and r is convex in g, a positive adjustment further increases the relative price of fertilizer to promote additional land use and decrease expected runoff (the adjustment is negative if g is concave).

The final three adjustment terms reflect pecuniary externalities, and would vanish in the absence of price effects (Shortle et al., 1998). Specifically, the third and fourth adjustment terms, $\sum_{k\neq i}\lambda^k(E\{\partial r^k/\partial g^k\}\zeta^{ki} - (E\{\partial r^k/\partial g^k\}g^k - E\{r^k\})\omega^{ki}\zeta^{ki})$, represent the marginal impacts of input and output price effects due to t^i (represented by $\omega_1^{ki}\zeta^{ki}$) on other sub-regions' pollution control costs. These adjustments are positive if, at the margin, the price effects of t^i decrease pollution control costs (and hence pollution) and negative otherwise. Analytically, the signs of these terms are ambiguous. However, it is likely that $\zeta^{ki} < 0$ and $\omega_1^{ki} > 0$ since (i) t^i decreases fertilizer use in the ith sub-region, decreasing w_2 and increasing quantity demanded in other sub-regions, and (ii) the ith sub-region's output effects increase *p*, increasing the demand for all inputs in other sub-regions. Given these signs, the third adjustment term is negative because the pecuniary externalities associated with t^i increase pollution control costs in other sub-regions. The sign of the fourth adjustment term depends on the convexity or concavity of runoff and is likely to be of less importance relative to the third adjustment term since land substitution is a secondary effect (relative to fertilizer reductions) and land markets are sub-regional.

The final term illustrates an interesting equilibrium result due to pecuniary externalities. Assuming $\zeta^{ki} < 0$, the effectiveness of t^i is reduced as the tax rates in other sub-regions are increased and the resulting pecuniary externalities increase the derived demand for fertilizer in sub-region *i*. Given that $\partial\pi^k/\partial x_2^k = t^k$, the final adjustment term indicates that as taxes in other sub-regions are increased, t^i must also increase to compensate for this reduced effectiveness. As we show below, this effect can have significant impacts on the resulting outcome.

Similar welfare impacts are reflected in the form of the optimal uniform fertilizer tax

$$t = \left[\lambda^k E\left\{\frac{\partial r^k}{\partial g^k}\right\} - \lambda^k\left(E\left\{\frac{\partial r^k}{\partial g^k}\right\}g^k - E\{r^k\}\right)\omega_1^{kk}\right]\gamma \tag{4}$$

where $\gamma = (dx_2^k/dt)/(\sum_{i=1}^n dx_s^i/dt)$ and all RHS values are evaluated at the second-best optimum. A single tax rate can generally only be used to achieve a single environmental goal as an equality (i.e., $E\{x_1^k r^k\} = \kappa^k$), and so there will be over compliance in all other sub-regions (i.e., $E\{x_1^i r^i\} < \kappa^i$ and $\lambda^i = 0, \forall i \neq k$). Consequently, the environmental impacts of pecuniary externalities are only valued in sub-region *k*, as is represented by the RHS of (4) through the term γ. Indeed, significant pecuniary externalities may be imposed on *k* if over compliance in other sub-regions produces appreciable market effects. Substitution externalities also exist in sub-region *k*, although it is more difficult to distinguish between the two types of externalities in the uniform case.

A quantitative comparison of the uniform and non-uniform taxes and their economic and equity impacts is not possible. Relative differences between the taxes depends on a number of factors, including environmental quality relationships, land-fertilizer substitution possibilities, and endogenous market effects. Empirical analysis is therefore necessary to make such comparisons.

An Application to North Central U.S. Corn Production

To obtain a more complete understanding of the efficiency and equity impacts of second-best fertilizer taxes, we develop empirical estimates the control costs and distributional effects of the incentives presented above for a model of corn production in the North Central U.S. Corn is a heavily fertilized crop and the North Central U.S., which includes Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin, accounts for approximately 65% of U.S. corn

Table I. Share data

		West	East	North	Southwest
Factor shares	Land	0.350	0.339	0.319	0.354
	Fertilizer	0.235	0.247	0.198	0.205
	Capital	0.277	0.284	0.327	0.341
	Labor	0.138	0.130	0.156	0.100
Production shares		0.522	0.207	0.244	0.047
Market shares	Domestic demand				0.79
	Export demand				0.21
	North central region				0.65

production. The heavy use of fertilizer in this region is thought to contribute to a number of nutrient management problems, such as the hypoxic zone in the Gulf of Mexico (CAST 1999). We divide the North Central region into four sub-regions: North (Michigan, Minnesota, Wisconsin), West (Iowa and Illinois), East (Indiana and Ohio), and Southwest (Missouri). Sub-regions are defined on the basis of soil productivity (expected corn yields) and along jurisdictional lines, in recognition that policies (particularly tax policies) may vary by jurisdiction.

Functional forms. Production uses a two-level, constant elasticity of substitution (CES) technology (Sato 1967) that exhibits constant returns to scale. Following prior work based on the two-level CES approach (Abler and Shortle 1992; Kawagoe, Otsuka and Hayami 1985; Hayami and Ruttan 1985; Thirtle 1985; Binswanger 1974), production is a function of a composite biological input (produced using land and fertilizer) and a composite mechanical input (produced using capital and labor). Corn demand is a first order approximation of actual demand. Estimates of the elasticity of demand for corn generally pertain to the entire U.S. market. Factor supplies take a constant elasticity form. Land supply is sub-region-specific while other factors are freely allocated through region-wide markets, given the long-run nature of the model. Finally, expected nutrient (i.e., nitrogen and/or phosphorous) runoff *per acre* for sub-region i is modeled as a quadratic function of *per acre* fertilizer application. Per acre runoff is increasing and convex in per acre fertilizer application.[6]

Data and model calibration. The model is calibrated using data in Table I. Cost shares are developed from corn cost of production data for North Central Region states for 1987–1989 (USDA-ERS).[7] A regionalized, composite demand elasticity is the share-weighted sum of domestic and export demand elasticities, $\eta = \delta(\eta_a n_d + \eta_e m_e)$, where η_d and η_e are domestic and export elasticities for the U.S. corn market, respectively, m_d and m_e are the shares of U.S. production going to

Table II. Distributions of unknown elasticity parameters

Parameter	Notation	Lower Bound	Upper Bound	Mean	Variance
Elasticity of substitution between land and fertilizer	σ_{12}	0.50	2.00	1.250	0.1875
Elasticity of substitution between labor and capital	σ_{34}	0.20	1.20	0.700	0.0833
Elasticity of substitution between composite inputs	σ	0.1	1.00	0.550	0.0675
Elasticity of land supply	ε_1	0.15	0.45	0.300	0.0075
Elasticity of output demand	η	–1.20	–0.45	–0.825	0.0469

domestic and export markets, respectively, and $0 < \delta < 1$ is the proportion of U.S. corn grown in the North Central region. The share of U.S. corn exported and the share produced in the North Central region are calculated as the average for 1987–1989 from Agricultural Statistics (USDA-NASS 1990).

Input and output prices are set equal to one so that output quantity equals revenue and input quantities equal costs. Quantity variables are scaled by dividing by output quantity (revenue). Because revenue equals cost with constant returns to scale, input quantities equal cost shares. Finally, outputs are converted to dollar terms by multiplying by base case industry revenue (since base case revenue always equals one).

Many elasticities needed to calibrate the model are not known with certainty. A review of relevant literature reveals a range of estimates for many important elasticities, including output demand, input substitution, and the land supply.[8] Most previous studies either ignore uncertainty by treating estimated parameters as though they were certain (e.g., Helfand and House 1995; Larson, Helfand and House 1996), or deal with uncertainties by performing a simple sensitivity analysis (i.e., calculating the optimal solution under a few different parameter values). Following Abler and Shortle (1995) and Davis and Espinoza (1998), a more robust sensitivity analysis is achieved by examining the distribution of model results (e.g., control costs) given parameter distributions inferred from the literature. All uncertain parameters are assumed to be uniformly and independently distributed, within bounds determined by a reasonable range of estimates (Table II).[9] We estimate the mean and standard deviation of model results using 1000 Monte Carlo simulations for each policy where each iteration represents a random draw of parameter values and parameter values are assumed known with certainty in each iteration.

Several parameters are assumed known with certainty: the elasticities of supply for fertilizer, labor, and capital. Long run labor supply elasticity estimates for U.S. agriculture range from 0.7 to 2.5 (Tyrshniewicz and Schuh 1969; Rosine and Helmberger 1974; Duffield 1990; Perloff 1991). A value of 3 is adopted because the model is regional and because corn production is not relatively labor intensive (e.g., compared to fruit or vegetable production). In the long run, the supply of capital and fertilizer to corn production in the North Central regions is assumed to be highly elastic. A value of 10 is adopted for these supply elasticities.

The runoff function parameters are generally unknown but can be placed within reasonable bounds (see endnote 6). For example, expected runoff is not likely to be more than 50% of total applied nutrients given a reasonable range of economic activity. The runoff function is calibrated by selecting a value for average runoff from a uniform distribution with bounds 0 and 0.5, and marginal runoff from a uniform distribution bounded from below by average runoff and from above by two times average runoff or one, whichever is smaller. These bounds follow from the construction of the non-decreasing, convex expected runoff function. The sensitivity of the model to variation in these parameters is assessed as part of the Monte Carlo analysis.

Simulations and Discussion

Results for both uniform and non-uniform taxes are reported in Tables III–V. In each case, results are reported as differences from a competitive base case with no intervention. All dollar values are calculated from initial total revenue of \$18.15 billion, assuming a corn price of \$2.83/bushel, and an average corn yield of 121 bushels/acre on 53 million acres. In general, the higher the standard deviation relative to the mean estimate, the more sensitive results are to variations in uncertain parameters. Mean estimates are generally consistent with prior empirical analysis of agri-chemical tax policies (Hrubovcak et al. 1990).

The *ex post* distributions of control costs (i.e. change in net private surplus), changes in consumer surplus and tax revenue, and changes in aggregate factor returns for each policy are presented in Table III. Differences in the relative economic performance of the non-uniform and uniform taxes are reported in the final column. A positive value in this column indicates that the affected group is expected to prefer the non-uniform tax to the uniform tax. As required by LeChatelier's Principle, the non-uniform tax is relatively more efficient than the uniform tax, producing lower control costs in 100% of the random samples. On average, the non-uniform tax is about 42.3% more efficient than the uniform tax, although the variability of this result is high.[10]

Although the non-uniform tax is more efficient, the two policies have mixed impacts for different groups receiving economic benefits from production. The expected change in surplus for consumers/taxpayers is negative for both policies because of higher commodity prices. However, tax revenues exceed the loss in consumer surplus in some cases. The change in surplus to consumers/taxpayers is positive for about 22% of random samples under the uniform tax and about 24% under the non-uniform tax. On average, the non-uniform tax costs consumers/taxpayers about 39.6% less than the uniform tax, although the vari-

Table III. Distribution of fertilizer tax consequences: Region-wide mean values, standard deviations, and percent of observations greater than zero

	Non-uniform	Uniform	Difference (Non-Uniform minus Uniform)
	(Values in Million $)		
Net private surplus	–70.32[a]	–121.76	51.45
	(23.64)[b]	(48.20)	(37.48)
	0.0[c]	0.0	100.0
Consumer surplus and tax revenue	–81.22	–134.14	52.92
	(128.34)	(179.42)	(63.30)
	24.3	21.7	87.3
Return to land	113.12	138.60	–25.49
	(156.86)	(197.70)	(52.96)
	75.9	75.2	27.4
Return to fertilizer	–60.02	–77.75	17.73
	(6.69)	(10.32)	(9.92)
	0.0	0.0	100.0
Return to capital	–7.55	–10.08	2.53
	(9.49)	(12.82)	(3.90)
	23.0	23.3	77.6
Return to labor	–10.87	–14.63	3.76
	(13.47)	(18.22)	(5.64)
	22.8	22.4	77.7

[a]Sample mean.
[b]Sample standard deviation.
[c]Percent of sample observations greater than zero.

ability of this result is high. Indeed, consumers/taxpayers are better off with the uniform tax for 12.7% of the random samples.

Fertilizer producers are clearly worse off under either tax scenario, with relatively little variation in results. On average, fertilizer industry returns are 22.8% higher for the non-uniform tax relative to the uniform tax, and the non-uniform tax produces higher fertilizer industry returns than the uniform tax for 100% of the random samples.

Owners of capital and labor resources are also expected to be worse off under either policy option, but these results only hold for about 77% of the random samples. There is a 23% chance that these resource owners will benefit from either tax policy. Returns to each factor are expected to be about 25% higher under the

Table IV. Change in return to land by sub-region under the tax policies

Policy scenario	Sub-region	Expected change (million $)	Expected percent change	% of Parameter vectors where change is > 0
Non-uniform tax	West	41.67	1.75	73.6
		(72.68)[a]		
	East	10.89	1.18	66.7
		(34.02)		
	North	30.33	2.75	82.5
		(32.64)		
	Southwest	6.45	3.06	81.6
		(7.70)		
Uniform tax	West	40.94	1.72	69.4
		(91.40)		
	East	3.38	0.37	55.6
		(37.16)		
	North	59.86	5.43	95.8
		(38.69)		
	Southwest	10.65	5.01	91.6
		(8.13)		
Difference between outcomes (Non-Uniform minus Uniform)	West	0.73	0.03	47.1
		(38.11)		
	East	7.51	0.81	61.8
		(22.25)		
	North	–29.53	–2.68	13.7
		(28.90)		
	Southwest	–4.20	–1.99	23.7
		(5.77)		

[a]Sample standard deviation.

non-uniform tax. However, this result is also highly variable. In fact, the uniform tax produces higher returns to capital and labor in approximately 22% of the random samples.

Landowners face different welfare effects. In aggregate, their welfare is expected to increase under either tax scenario; however, these results only hold for about 75% of the random samples. Average land rents are 18% higher for the uniform tax than the non-uniform tax, although the non-uniform tax does produce higher aggregate land rents in 27.4% of the random samples.

The distribution of results for changes in land rents under each policy is broken down by sub-region in Table IV to provide a clearer picture of gains and losses to landowners under each policy scenario (percentage changes in outcomes are presented to ease comparison between sub-regions of different sizes). Expected welfare impacts to landowners are positive in all sub-regions (for both tax policies), but highly variable. For each policy, the ranking of expected *percentage* change in returns to landowners is $\Delta R_1^{North} > \Delta R_1^{Southwest} > \Delta R_1^{West} > \Delta R_1^{East}$, where ΔR_1^i is the expected percentage change in sub-region *i*'s land rents (variation is smallest in the North and Southwest, where gains occur for 81.6% to 82.5% and 91.6% to 95.8% of the random samples, for the non-uniform and uniform taxes, respectively). This ranking holds for more than 99% of random samples for the uniform tax, but for only about 60% of the random samples under the non-uniform tax.

The difference in expected gains between sub-regions is narrower with the non-uniform tax. In the West and East, expected land rents are higher under the non-uniform tax, although land rents are only larger under the non-uniform tax for 47.1% and 61.8% of the random samples for the West and East, respectively. In the North and Southwest, expected land rents are higher under the uniform tax, with less variability (land rents are larger under the uniform tax for 86.3% and 76.3% of the random samples, respectively).

Uniform policies are often touted as being more equitable than non-uniform policies. But ironically, the non-uniform taxes result in a more uniform dispersion of landowner gains across sub-regions than the uniform tax, albeit with a smaller aggregate increase in land rents. Moreover, the uniform tax rate of 33 percent of the initial price of fertilizer is considerably higher than any of the non-uniform rates, which vary only slightly across sub-regions (ranging from 23 percent in the East to 26 percent in the North; see Table V).

A more comprehensive understanding of these results can be gained by considering how various producers respond to a fertilizer tax and how tax-induced pecuniary externalities affect fertilizer tax rates and returns to land across sub-regions. Land use and hence the return to land increase to the extent that the substitution effects of land for fertilizer dominate output effects of a tax. On average, this occurs in every sub-region because the mean elasticity of substitution between land and fertilizer is relatively high and the mean elasticity of output demand is relatively low. However, the relative magnitudes of substitution and output effects vary significantly across sub-regions. In our empirical analysis, technological heterogeneity is the key underlying source of variation in producer responses to the fertilizer tax. East and West producers, whose production technologies are designed around relatively intensive fertilizer use, respond to a given tax rate by reducing output to a larger degree than North and Southwest producers, whose technologies are relatively less dependent on fertilizer. In contrast, North and Southwest producers find substitution of fertilizer for land and other inputs to be less costly than East and West producers.

Table V. Distribution of quantity and price changes under the tax policies

	Non-uniform tax					Uniform tax				
	Expected percent change in quantity				Expected Percent Change in Price	Expected percent change in quantity				Expected Percent Change in Price
	West	East	North	Southwest		West	East	North	Southwest	
Output	–4.24	–4.65	–3.14	–3.30	5.20	–6.06	–7.09	–2.54	–3.58	6.95
	(1.47)[a]	(1.79)	(1.74)	(1.73)	(1.38)	(1.44)	(1.59)	(1.35)	(1.27)	(2.14)
Land	0.36	0.25	0.69	0.63	*	0.35	–0.07	1.35	1.05	**
	(0.67)	(0.82)	(0.79)	(0.79)		(0.83)	(0.91)	(0.96)	(0.88)	
Fertilizer	–14.64	–14.69	–14.54	–14.55	–1.57	–19.68	–20.58	–15.68	–17.20	–2.08
	(2.84)	(2.85)	(2.93)	(2.89)	(0.19)	(2.67)	(2.77)	(2.22)	(2.33)	(0.31)
Capital	–1.67	–2.09	–0.55	–0.70	–0.14	–2.74	–3.81	0.90	–0.16	–0.19
	(2.02)	(2.42)	(2.45)	(2.45)	(0.18)	(2.41)	(2.50)	(2.51)	(2.39)	(0.25)
Labor	–1.55	–1.96	–0.41	–0.56	–0.44	–2.56	–3.64	1.09	0.02	–0.60
	(1.88)	(2.31)	(2.32)	(2.33)	(0.54)	(2.20)	(2.29)	(2.27)	(2.17)	(0.74)
Tax Rate[b]	23.5	23.0	26.2	25.2		32.8[c]				
	(7.15)	(6.98)	(8.34)	(7.45)		(9.90)				

*Land markets are sub-regional. Percent change in prices (standard deviations) are: West, 1.24 (2.18); East, 0.84 (2.67); North, 2.32 (2.50); Southwest, 2.11 (2.53).

**Land markets are sub-regional. Percent change in prices (standard deviations) are: West, 1.22 (2.74); East, 0.25 (2.91); North, 4.57 (2.93); Southwest, 3.50 (2.66).

[a] Sample standard deviation.

[b] Percent of initial price of fertilizer.

[c] Rate is uniform across sub-regions.

The effect of technological heterogeneity in the absence of price effects and associated pecuniary externalities can be estimated by holding non-land input and output prices constant (i.e., when the absolute value of output demand and non-land input supply elasticities approach infinity). We allow land prices to vary because land is spatially fixed and may vary in value even if policy is applied only to a small geographic area, and because land price changes do not create pecuniary externalities between sub-regions. Table VI provides selected model results when various (combinations of) market prices are held constant. Contrasting results with and without price effects and pecuniary externalities provides significant additional insight on the role of the price effects and pecuniary externalities in determining fertilizer tax rates and returns to land for both the non-uniform and uniform policies.

First, consider fertilizer tax rates. With output and all non-land input prices held constant, non-uniform tax rates are roughly one-third of the tax rates when all prices are endogenous, and the uniform tax rate is one-fourth of the tax rate when all prices are endogenous. This illustrates the extent to which tax rates must be adjusted to compensate for pecuniary externalities that limit the effectiveness of the tax, especially in the uniform case.

Pecuniary externalities are created by both input and output price changes. For example, a fertilizer tax in one sub-region encourages producers in that sub-region to reduce fertilizer use. The result is a reduction in the price of fertilizer, which encourages more fertilizer use and hence more runoff in all sub-regions, other things being equal. A fertilizer tax also encourages output reduction which increases the equilibrium output price and encourages greater use of all inputs and hence expected runoff in all sub-regions, other things being equal. In both cases, tax rates must be raised in other sub-regions to compensate which, in turn, creates pecuniary externalities as well. This cycle results in escalating tax rates until an equilibrium is reached. From Table VI, it is clear that output price effects play a greater role in determining tax rates than do non-land input price effects. With only the output price held constant, tax rates are much lower than when only non-land input prices are fixed. The relative importance of output market price effects is not surprising given that output demand is inelastic while non-land input supplies are quite elastic.

The effect of pecuniary externalities on the uniform tax rate is even greater. With prices held constant, the optimal uniform tax rate equals the highest non-uniform tax rate because each sub-region must reduce runoff by 20 percent. The uniform tax rate cannot be lower than the highest non-uniform rate without violating the environmental constraint in at least one sub-region. There is no reason to set the uniform tax rate higher than the highest non-uniform rate because there are no pecuniary externalities. Establishing a uniform tax rate equal to the highest non-uniform rate is equivalent to increasing non-uniform tax rates in three of four sub-regions (East, West, and Southwest). With endogenous prices, increasing these sub-regional tax rates creates pecuniary externalities, resulting in increased

Table VI. Tax rates and returns to land under non-uniform and uniform fertilizer tax holding various prices constant

	Tax rates (percent of initial fertilizer price)					Percent change in returns to land									
	Non-uniform				Uniform	Non-uniform					Uniform				
	W[a]	E	N	SW		W	E	N	SW	CV[b]	W	E	N	SW	CV
Prices Endog. (Tables 4–5)	23.5	23.0	26.2	25.2	32.8	1.8	1.2	2.8	3.1	1.05	1.7	0.4	5.4	5.0	2.42
Non-land prices fixed	10.6	10.2	11.4	11.5	11.5	–8.4	–8.8	–8.4	–7.9	–0.039	–9.1	–9.9	–8.5	–8.0	–.083
Output price fixed	13.1	12.7	14.4	14.1	14.6	–7.5	–7.9	–7.3	–7.0	–0.046	–8.3	–9.2	–7.1	–7.1	–0.11
Non-land input prices fixed	21.6	21.2	24.5	23.4	27.2	1.6	1.0	2.8	2.6	0.36	1.4	0.3	5.3	4.1	0.71

[a] W = west, E = east, N = north, and SW = southwest.
[b] CV = coefficient of variation of percent changes in returns to landowners.

expected runoff and a violation of the environmental constraint in the North and possibly other sub-regions. Specifically, higher tax rates prompt producers in three sub-regions to reduce output and fertilizer use, increasing the output price and reducing the fertilizer price. These price changes, or pecuniary externalities, increase the derived demand for fertilizer and other inputs in the North sub-region, ultimately increasing expected runoff. To satisfy the runoff constraint in the North sub-region, the uniform tax rate must be larger than 26 percent. Moreover, because the tax is uniform, increasing the tax rate initiates a new cycle of pecuniary externalities that eventually results in a much higher uniform tax rate of 33 percent.

Now consider returns to land. When prices are held constant, returns to land fall by 5–7 percent for both policies in all sub-regions (Table VI). With price effects, the change in return to land is, on average, positive for all sub-regions for both the non-uniform and uniform policies. These differences illustrate the extent to which pecuniary externalities affect land returns. Table VI indicates that returns to land, like tax rates, are sharply reduced (relative to the price endogenous case) by holding only output price constant but are reduced only marginally when only non-land input prices are held constant.

Pecuniary externalities, particularly those associated with output price changes, also significantly affect sub-regional differences in returns to land. Pecuniary externalities are generated among all sub-regions; however, the largest of these externalities are transmitted from the East and West sub-regions (where output effects are greatest) to the North and Southwest. As a result, output reduction is larger in the East and West and smaller in the North and Southwest than would be the case without pecuniary externalities, with a concomitant effect on returns to land. Pecuniary externalities are especially large for the uniform tax. The higher uniform tax rate produces proportionately larger pecuniary externalities, resulting in larger divergence in output effects and returns to land among sub-regions. The increased divergence in output effects can be seen by comparing output reductions under the non-uniform and uniform tax policies (Table V). Net output reductions are significantly more divergent between sub-regions under the uniform policy than under the non-uniform policy. The net output effect is substantially larger in the East and West sub-regions under the uniform tax and moderately larger for the Southwest. In the North sub-region, the net output effect is actually smaller under the uniform policy, despite the higher tax rate, illustrating the strength of pecuniary externalities. To demonstrate formally how the dispersion of land returns varies by sub-region, we calculate the coefficient of variation among sub-regional returns to land for scenarios reported in Table VI. The absolute value of the coefficient of variation among sub-regional percentage changes confirms that divergence in returns is, in fact, much larger when market prices are endogenous and the tax is uniform.

Conclusions

This paper has highlighted some important efficiency and equity effects of uniform and non-uniform, second-best environmental incentives, as well as the key role that markets play in determining the resulting outcome. Whereas pecuniary externalities are often dismissed as not having efficiency impacts, we find their efficiency-related impacts to be significant in the case of second-best instruments. Price effects and associated pecuniary externalities can be extremely important in determining optimal environmental policies as well as equity outcomes. Indeed, understanding price effects and pecuniary externalities is critical in assessing the relative efficiency and equity of the uniform and non-uniform tax policies in our model.

Our analysis is largely exploratory and further research is needed in at least two respects. First, other policies, such as green payments and regulation should be investigated. Given the underlying importance of farmer economic interests in policy formulation, non-tax policy options may be quite important. Moreover, while conclusions are based on the central tendencies of the model and can be thought of as "best estimates" of fertilizer tax rates and associated equity effects, the Monte Carlo analysis reveals a significant degree of uncertainty regarding both optimal tax rates and equity effects. One criteria on which policies may be judged is their sensitivity to underlying uncertainties about the structure of production or environmental effects. Future research should focus, in part, on comparing the robustness of alternate policies to underlying uncertainties.

Second, other policy objectives should be considered. For example, policy makers may be less concerned with the geographic origin of runoff than with the total amount of runoff from agriculture. A good example is nonpoint control in the Mississippi basin to reduce the zone of hypoxic water in the Gulf of Mexico, where a relevant constraint would be to reduce the total amount of nitrogen transported to the Gulf. In this case, pollution control could be directed to sub-regions with low control costs, reducing overall costs. Even if overall costs can be reduced, serious equity issues, worthy of careful consideration, may arise.

Notes

1. We use the term runoff to refer to all types of surface runoff and leaching.
2. A likely reason NPSP policy goals are often defined in terms of expected runoff is significant uncertainty about the fate and transport of nutrients from fields to water resources. Because runoff cannot be monitored accurately at reasonable cost, determination of whether or not (2) is satisfied will depend on the use of simulation models (e.g., EPIC, AGNPS, or other similar models) that estimate runoff levels given specific production choices.
3. Second-best policies may improve efficiency in some respects by reducing administrative costs and also incentives for arbitrage between sub-regions (Shortle et al. 1998).
4. If land use was also targeted under both the uniform and non-uniform scenarios, then pecuniary externalities would only be relevant in the uniform tax case.

5. Optimal tax rates, both in the non-uniform and uniform cases, are of the same form as optimal taxes designed to solve the collective environmental goal, $\sum_i E\{r^i x_1^i\} \leq \kappa$, the only exception being that $\lambda^i = \lambda^k \forall k$ under a collective goal. The types of benefits and costs reflected in the taxes of this paper are therefore not unique to the current setup.
6. Convexity of $E\{r^i\}$ is consistent with Weinberg and Kling (1996) and others. For example, fertilizer nitrogen accounts for the majority of fertilizer applied in corn production and roughly 70% of fertilizer applied to corn in the North Central region. Nitrogen not taken up by the crop (residual nitrogen) may be lost to the environment (Sanchez and Blackmer 1988; Hallberg 1987), and evidence suggests these losses increase as the amount of residual nitrogen in the soil profile increases (Hallberg 1987). A variety of studies indicate total nitrogen inputs to cropland (from all sources, including fertilizer) significantly exceeds nitrogen uptake by crops, including crop residue (NRC 1993). The amount of fertilizer nitrogen taken up by crops, including the portion in crop residues, is rarely greater than 70% and is typically closer to 50% (Keeney 1982). Peterson and Frye (1989) estimated that nitrogen fertilizer applied in corn production exceeded nitrogen harvested with the grain by 50% in every year between 1968 and 1988. Thus, it is reasonable to assume that between one-third and one-half of all nitrogen fertilizer used in corn production is left as residual in the soil. At high rates of fertilizer application, when crop yields are near optimum levels, as little as 10% of the marginal unit of fertilizer nitrogen is taken up by the crop, leaving 90% as residual which may be lost to the environment (NRC 1993). Thus, the amount of residual nitrogen created from the marginal unit of nitrogen fertilizer exceeds that of the average unit of nitrogen fertilizer. If losses to the environment (runoff) increase at a linear or increasing rate in residual nitrogen, then nitrogen runoff will be convex in fertilizer nitrogen application. To assume that losses to the environment are concave in residual nitrogen, we would have to argue that runoff declines as residual nitrogen increases – a possibility we believe is remote.

   Phosphorous is also a major nutrient of environmental concern. Losses generally occur when phosphorous attached to soil particles is removed with sediment during soil erosion. Sharpley (1980) estimates phosphorous losses increase approximately linearly with fertilizer application rates.
7. More recent data is not statistically reliable at the state level.
8. Input substitution elasticity estimates are found in Binswanger (1974); Chambers and Vasavada (1983); Fernandez-Cornejo (1992); Hertel (1989); Kawagoe, Otsuka, and Hayami (1985); Ray (1982); Thirtle (1985). Land supply elasticity estimates for corn production are found in Chavas and Holt (1990); Holt (1992); Lee and Helmberger (1985); Tegene, Huffman, and Miranowski (1988). Corn demand elasticities are from a survey by Gardiner and Dixit (1986) and more recent estimates by Haley and Krisoff (1987) and Holt (1992). The domestic corn demand elasticity is assumed to range from 0.3 to 0.7, while the export demand elasticity is assumed to range from 1 to 3. These values are used to create the composite lower and upper bounds for η.
9. The uniform distribution is sometimes used when the actual distribution is unknown. This method is used for its relative simplicity and intuitive appeal.
10. The expected percentage difference in relative efficiency is calculated for simplicity as the expected difference in control costs, divided by the expected control cost of the more efficient instrument. By Jensen's inequality, this value differs slightly from the true value.

Appendix

Consider a fertilizer tax, t^i, that varies by sub-region. Assuming an interior solution, the first order conditions for after-tax profit maximization are $\partial\pi^i/\partial x_2^i = t^i$ and $\partial\pi^i/\partial x_j^i = 0\ \forall i, \forall j \neq 2$. Input demand in sub-region *i* is a function of t^i and input and output prices, $x_j^i(t^i, P_p, w_p^i)\forall i, j$, where P_p is the price faced by producers (output supply price), and

w_p^i is the vector of input prices faced by producers in sub-region *i*. In equilibrium, markets clear and all producers and consumers face the same set of prices, which are functions of the tax rates from each sub-region, i.e., $P_p = p(t^1, \ldots, t^n)$, $w_{1P}^i = w_1^i(t^1, \ldots, t^n)$, $w_{jP} = w_j(t^1, \ldots, t^n)\ \forall i, \forall j \neq 1$.

Optimal input taxes are determined by plugging the equilibrium input demand functions, $x_j^i(t^i, p(t^1, \ldots, t^n), w(t^1, \ldots, t^n)) \forall i, j$, into the social objective function (1), and choosing tax rates to maximize (1) subject to the constraints defined by (2). The shadow values associated with the constraints defined by (2) are λ^i. Assuming an interior solution, the first order conditions with respect to the fertilizer taxes are

$$\frac{\partial V}{\partial t^i} = \sum_{k=1}^{n} \sum_{j=1}^{m} \frac{\partial \pi^k}{\partial x_j^k} \frac{dx_j^k}{dt^i} - \sum_{k=1}^{n} \lambda^k E \left\{ \frac{\partial r^k}{\partial g^k} \frac{\partial g^k}{\partial x_1^k} \frac{dx_1^k}{dt^i} + \frac{\partial r^k}{\partial g^k} \frac{\partial g^k}{\partial x_2^k} \frac{dx_2^k}{dt^i} \right\} = 0 \quad \forall i \tag{A1}$$

where $dx_j^i/dt^i = \partial x_j^i/\partial t^i + (\partial x_j^i/\partial p)(\partial p/\partial t^i) + \sum_{l=1}^m (\partial x_j^i/\partial w_l^i)(\partial w_l^i/\partial t^i) \forall j$, and $dx_j^k/dt^i = (\partial x_j^k/\partial p)(\partial p/\partial t^i) + \sum_{l=1}^m (\partial x_j^k/\partial w_l^k)(\partial w_l^k/\partial t^i) \forall j, \forall k \neq i$ (for a uniform tax, $dx_j^i/dt = \partial x_j^i/\partial t + (\partial x_j^i/\partial p)(\partial p/\partial t) + \sum_{l=1}^m (\partial x_j^i/\partial w_l^i)(\partial w_l^i/\partial t) \forall i, j$). The optimal tax rate (3) is derived by using (A1) along with the relationships from the profit maximizing conditions. A similar method can be used to derive the optimal uniform tax rate (4), where *k* is the sub-region with the highest marginal pollution control costs.

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